金ナノ粒子ーナノ光ファイバ結合系の偏光に対するキラル性の研究

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金ナノ粒子—ナノ光ファイバ結合系の偏光に対するキラル性の研究

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Study of the chiral polarization response of a gold nanoparticle coupled to an optical nanofiber

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In this thesis we measured the polarization response function of an optical nanofiber optical interface. By introducing a gold nanosphere to the nanofiber surface, we were able to measure light from a polarization-controlled source scattered by the nanosphere into the nanofiber guided modes. The results correspond well with theoretical calculations. We also show mathematically that the chirality of nanofiber interfaces follows a universal scaling law. We used the scaling law to summarize data taken for different nanofiber diameters and nanosphere positions.

1. Background and motivation of this research

Quantum communication is expected to be a major part of next generation information technology. To realize quantum communication, establishing a “quantum network” is essential. For a realization of a quantum communication, optical nanofiber interfaces, i.e. optical nanofibers combined with quantum emitters such as atoms, quantum dots, etc, have recently become known as promising tools. Optical nanofibers are tapered optical fibers waist diameters are sub-wavelength relative to visible light (300 ~ 500 nm). At the nano-region, a large amount of the guided mode of the optical fiber exists around the surface of the fiber and photons emitted from quantum emitters at the surface of the fiber couple to the fiber with relatively high efficiency. However, the coupling direction of the photons is unpredictable because spontaneous emission is a random process. This causes 50% loss given that our desire is to send the photon to a receiver at a given end of the fiber.

However, very recently, the research group of Rauschenbeutel in Vienna demonstrated that optical nanofibers have the property of chirality in 2014 [1]. They showed that circularly polarized light emitted from a dipole emitter coupled to either direction of the optical nanofiber, with the propagation direction determined by the sense of circular polarization. This property can solve the crucial problem discussed above.

Here we characterized the chiral coupling property of optical nanofiber interfaces using a more general method. Furthermore, we showed that the chiral response of an optical nanofiber can be described by a universal scaling law and we summarized our experimental results using this scaling law. In this article, we focus on the results of the characterization of the chiral coupling of the optical nanofiber.

2. Principle of chiral coupling

To understand the chiral behavior of an optical nanofiber, the existence of a longitudinal field component in the nanofiber guided modes should be appreciated. That is, the fundamental guided mode of an optical nanofiber has a non-negligible electric field component which is parallel with the direction of propagation of light inside the fiber. Moreover, this longitudinal component is $\pi/2$ out of phase to the transverse component and the sign depends on the propagation direction. As a result, the guided mode of the optical nanofiber gives rise to elliptically polarized

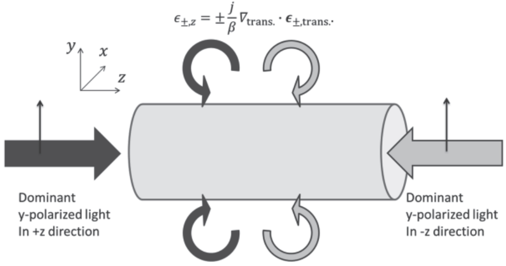

Fig. 1: A schematic figure of the electric field polarization of the fundamental mode of an optical nanofiber.

electric fields near the surface of the fiber as illustrated in Fig. 1.

Suppose we introduce a point dipole (note that quantum emitters such like atoms and quantum dots can be assumed to be point dipoles) on the top surface of the optical nanofiber with left circular polarization. Then, it is found that the coupled electric field couples mainly to the +z direction. We calculated the intensities of the coupled electric fields with respect to all polarization states of the point dipole and mapped the calculated intensities on the Poincaré spheres as shown in Fig. 2. We call this response plotted on a Poincaré sphere a *polarization response function* (PRF). Comparing with the case which shows no chiral property, chirality can be characterized by rotation angle χ of the PRFs on the Poincaré spheres. In this thesis, our goal was to measure the PRF experimentally.

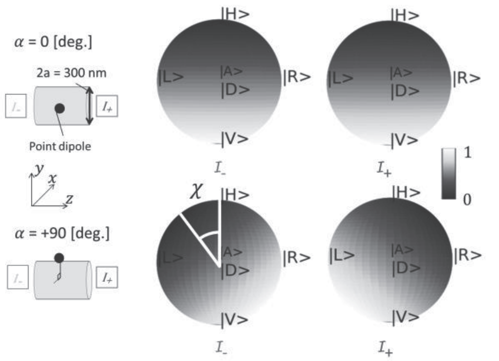

Fig. 2: Theoretical calculations of the coupling intensities of a point dipole on the surface of an optical nanofiber.

3. Experimental method for reconstructing the PRF

We measured the PRFs explained above by adapting and expanding a method used in [1]. We deposited a gold nanosphere (GNS) (diameter 150 nm) on the surface of an optical nanofiber fabricated in our laboratory and illuminated the GNS with light from a polarization-controlled laser source. By measuring the intensities of the light scattered from the GNS and coupled to the guided modes of the fiber, we could reconstruct the PRF. Because of its isotropy, light scattered from a single GNS preserves the polarization of the input light. Additionally, because the GNS was small relative to the light wavelength, it approximated a point dipole. Furthermore, GNSs have a strong plasmonic resonance and this property allowed us to perform the measurement with high signal-to-noise ratio.

4. Results: Measurement of the PRF

Experimental results are shown in Fig. 4. Upper spheres on left and right sides show experimentally obtained PRFs and lower spheres are theoretically calculated results using parameters measured by scanning electron microscope (SEM). The theoretical and experimental results show good qualitative and quantitative correspondence.

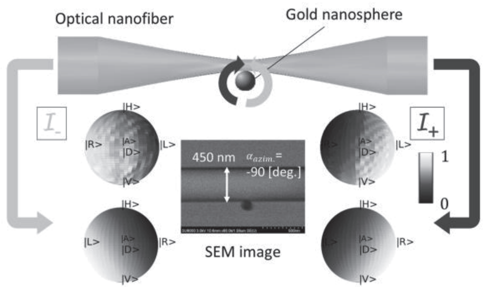

Fig. 3: Comparison of experimentally reconstructed PRFs (upper spheres) and the corresponding theoretical calculations (lower spheres). The image of the optical nanofiber and the GNS taken by scanning electron microscope (SEM) is shown in the middle of the figure.

5. Conclusion

We studied the chiral coupling of an optical nanofiber and found a new characterization method of the chirality using PRFs. We showed that the experimental results corresponded to the theory. We believe that this study will be useful when we compare the chiral properties among the other types of nano-scale waveguides which show chiral behavior (so-called "chiral nanowaveguides") quantitatively.

We are planning to study a couple of topics related to the gold nanoparticle-optical nanofiber coupled system. One of the plans is to combine a gold nanoparticle with a quantum dot and measure the enhancement of spontaneous emission of the quantum dot by the plasmonic resonance of the gold nanoparticle through an optical nanofiber. We expect that this will allow the creation of more efficient nanofiber interfaces, and also create a new platform for the study of quantum plasmonics

Reference

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